Quark-antiquark pair production in heavy ion collisions

K. Kajantie

keijo.kajantie@helsinki.fi

University of Helsinki, Finland

BNL, 9 May 2006

Work with F. Gelis and T. Lappi

Motivation, background

- QCD matter formed at RHIC seems to be in local thermal equilibrium

- What about chemical equilibrium: $g = g_B + \frac{7}{8}g_F = 16 + \frac{21}{2}N_f$?

- Prejudice: initial state dominantly gluonic so the system should be far from chemical equilibrium

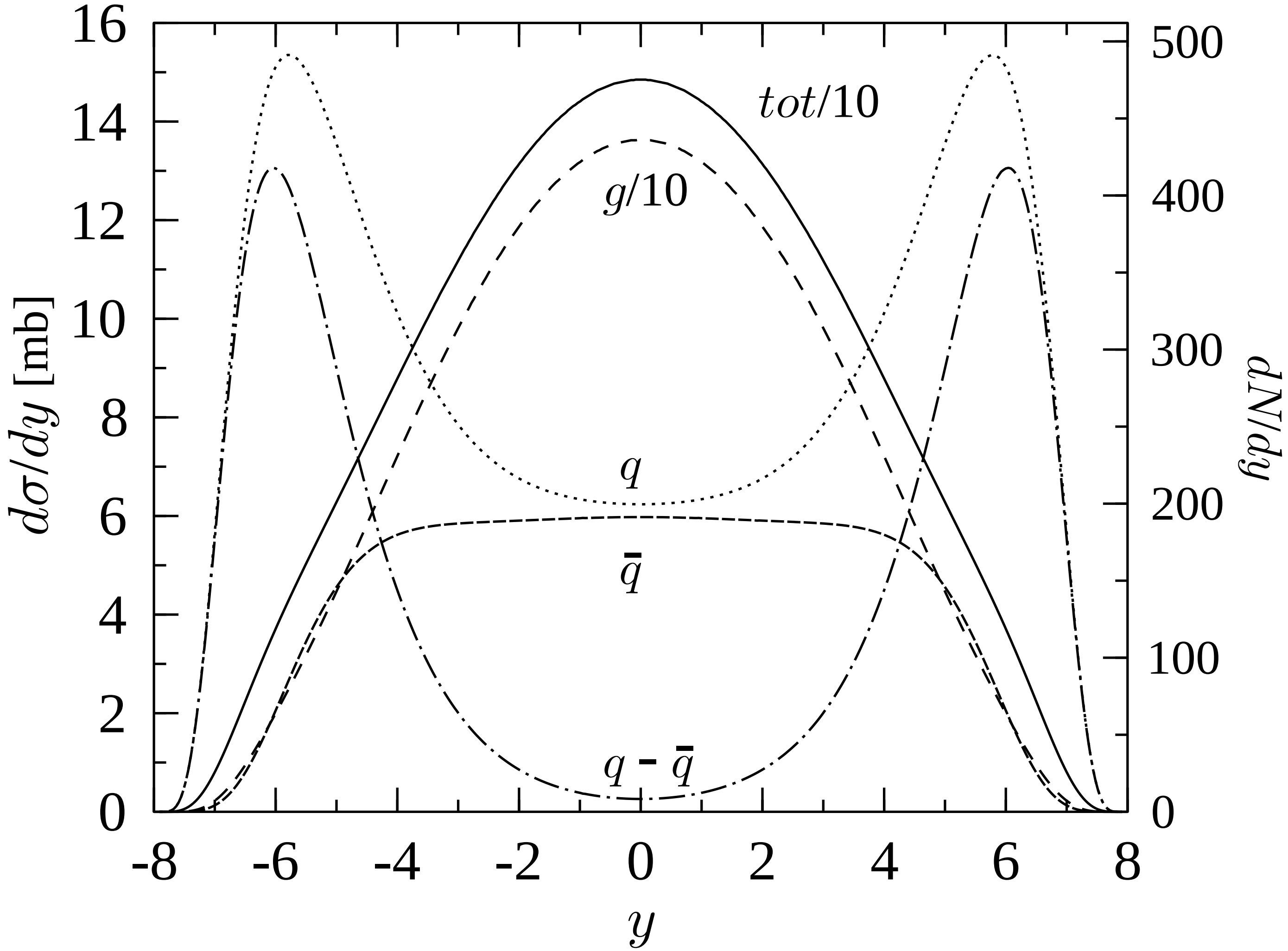
- Quantitatively? Can one compute the rate of (light) $q\bar{q}$ production?

- Might be important for thermal dilepton rates.

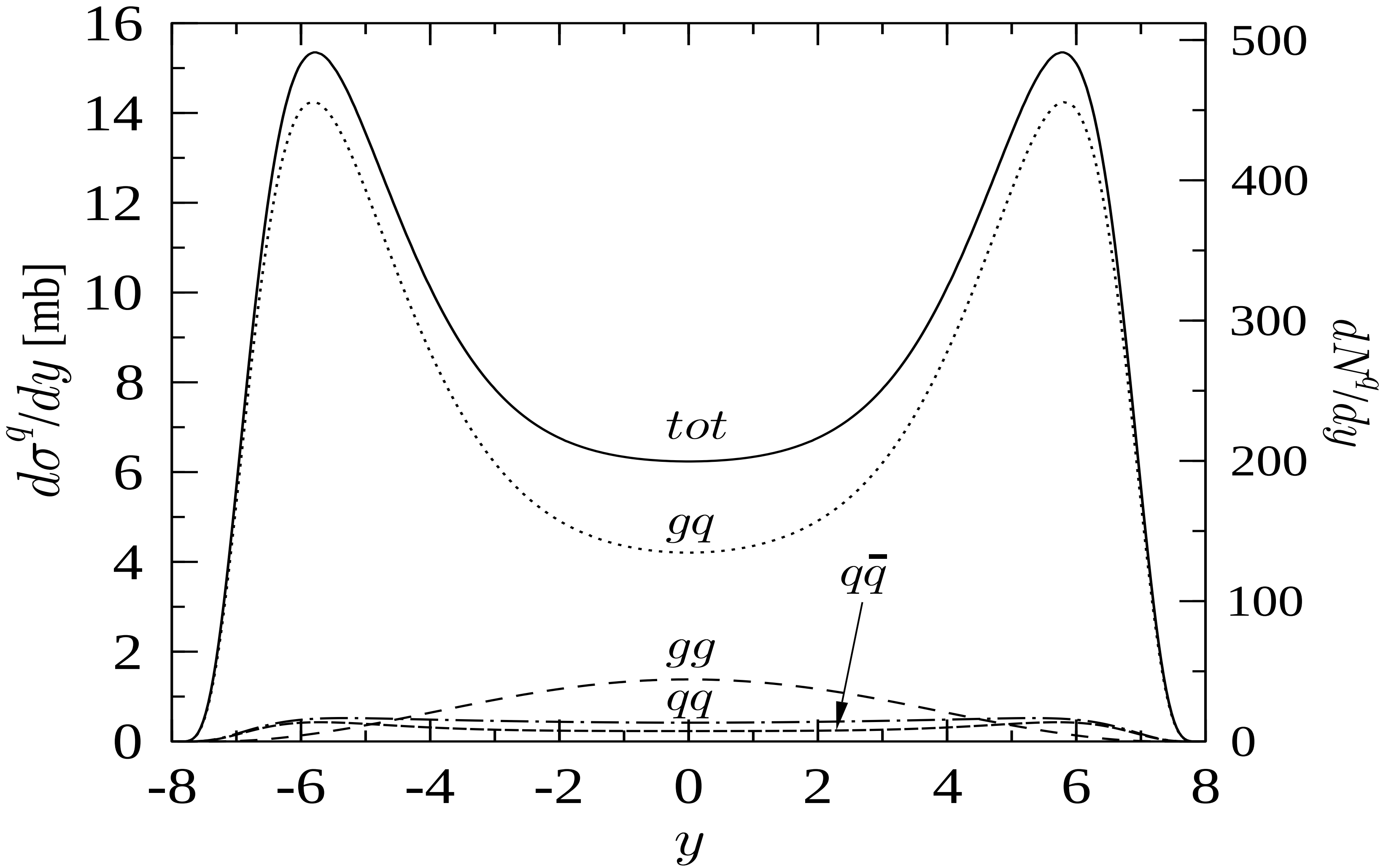
Standard QCD perturbation theory

Inclusive cross sections $p + p \to \mathrm{gluon}, \mathrm{quark}(p_T > 2\,\mathrm{GeV}) + X$ at $\sqrt{s} = 5500$ GeV

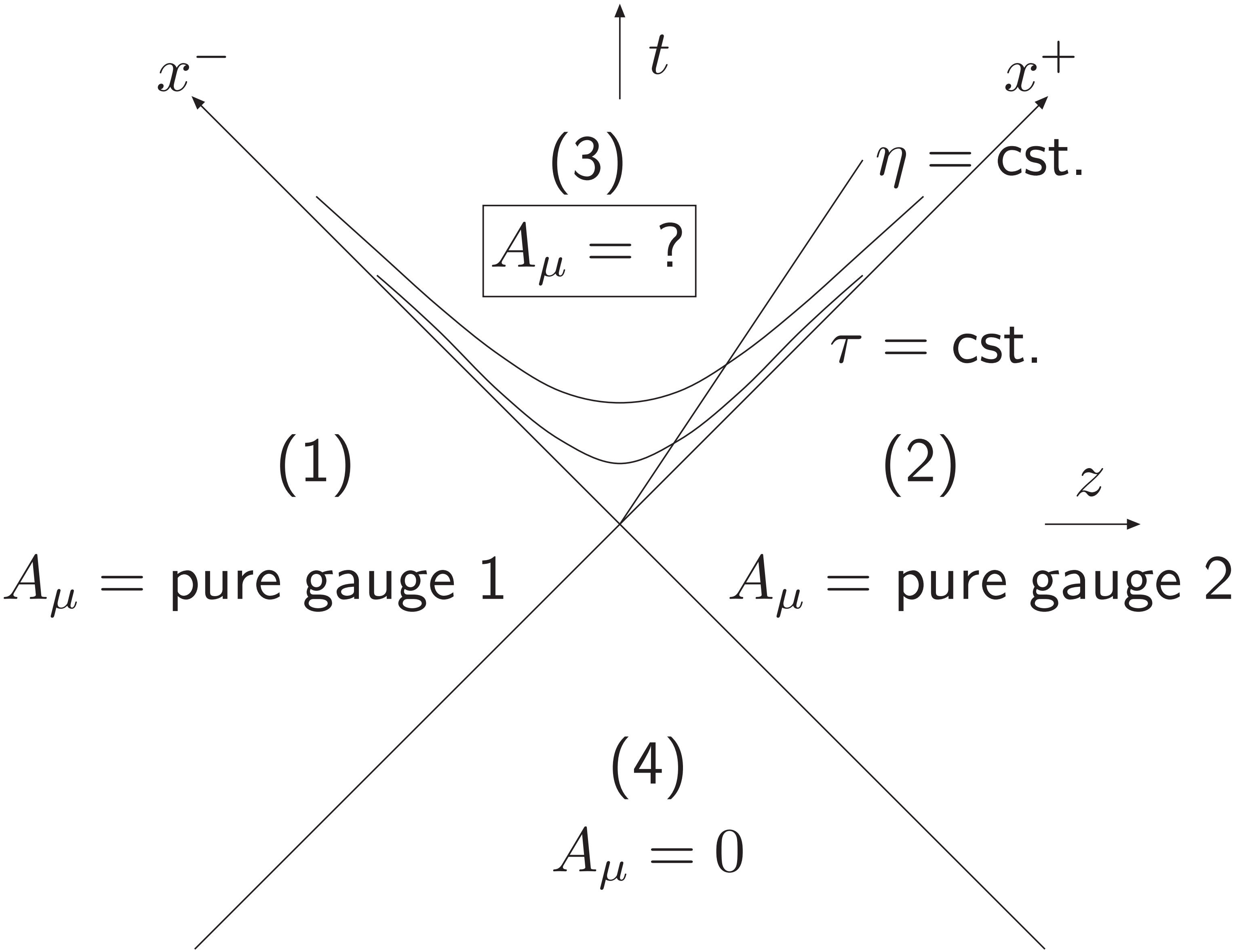
Eskola-Kajantie, nucl-th/9610015



The quarks come dominantly from gluons, $g + q \rightarrow g + q$:



Classical (+ quantum initial condition) field model:



For $\tau > 0$ want

$$A_\mu(\tau,\eta,\mathbf{x}_T) = (\ \underbrace{A_\tau = 0}_{\text{gauge choice}}\ , \underbrace{A_\eta(\tau,\mathbf{x}_T)}_{\sim\text{longit.}}, \mathbf{A}_T(\tau,\mathbf{x}_T))$$

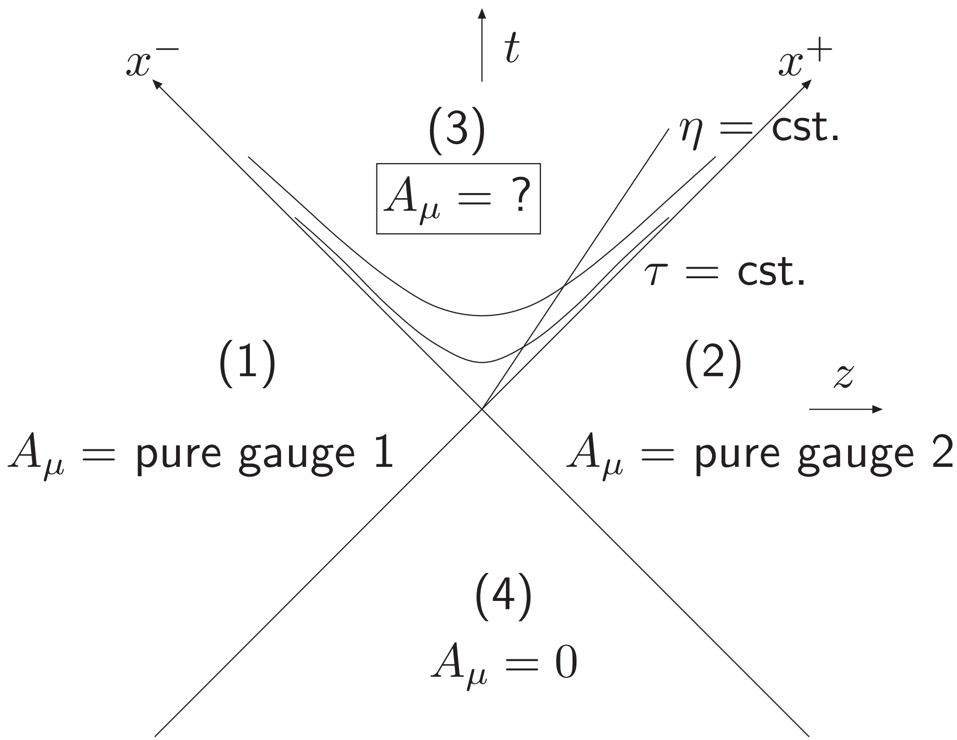
$\Rightarrow$ energy in and number of gluons. Solve numerically from $[D_\mu, F_{\mu\nu}] = 0$ with the remarkable initial condition from matching to two vacua below the light cone:

$$\begin{aligned} A^i(\tau=0,\mathbf{x}_T) &= A^i_{\text{vac1}}(\mathbf{x}_T) + A^i_{\text{vac2}}(\mathbf{x}_T), \\ A^\eta(\tau=0,\mathbf{x}_T) &= \frac{1}{2} ig[A^i_{\text{vac1}}(\mathbf{x}_T), A^i_{\text{vac2}}(\mathbf{x}_T)]. \end{aligned}$$

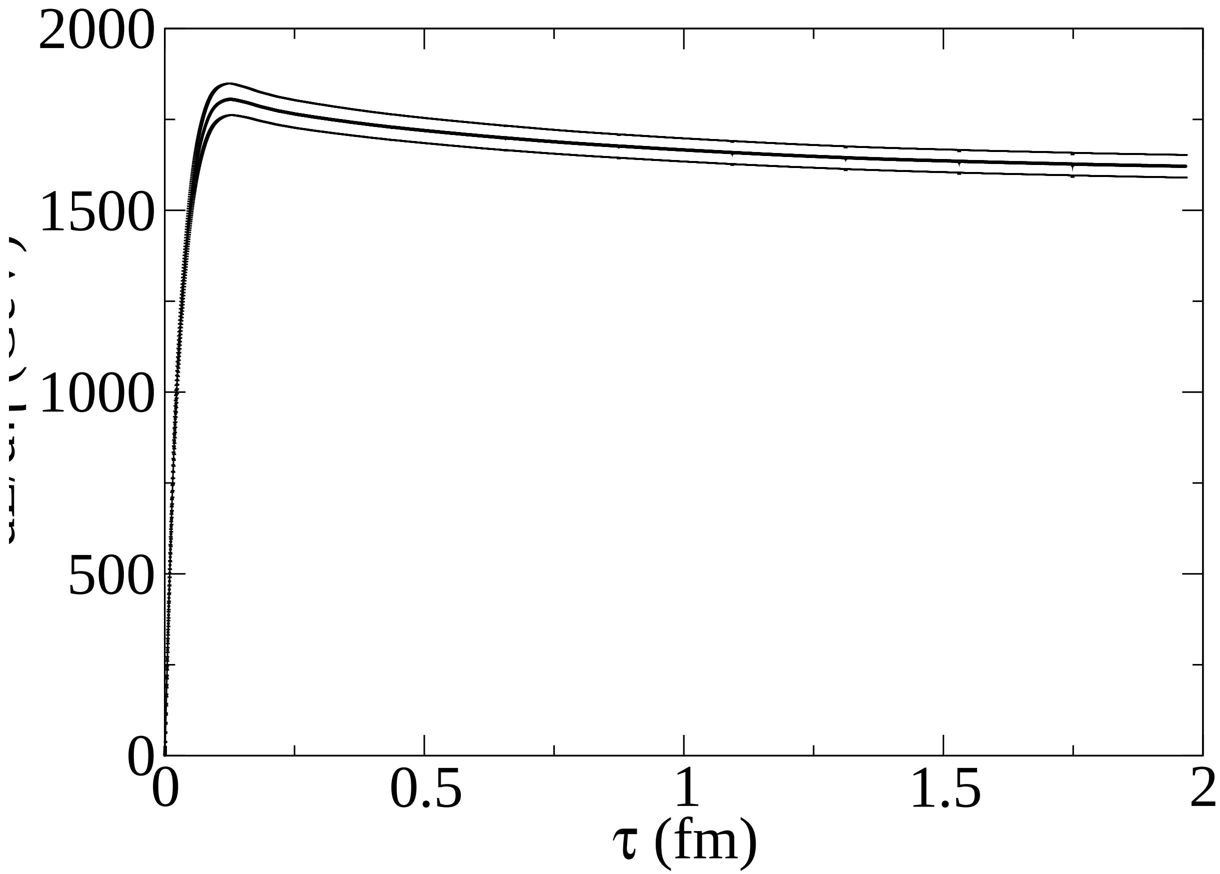
$A_i^{\text{vac}}(\mathbf{x}_T) = U(\mathbf{x}_T)\partial_i U^{-1}(\mathbf{x}_T)$,

$U = e^{i\Lambda}, \quad -\partial_T^2\Lambda = g\rho$,

$\rho =$ stochastic source.



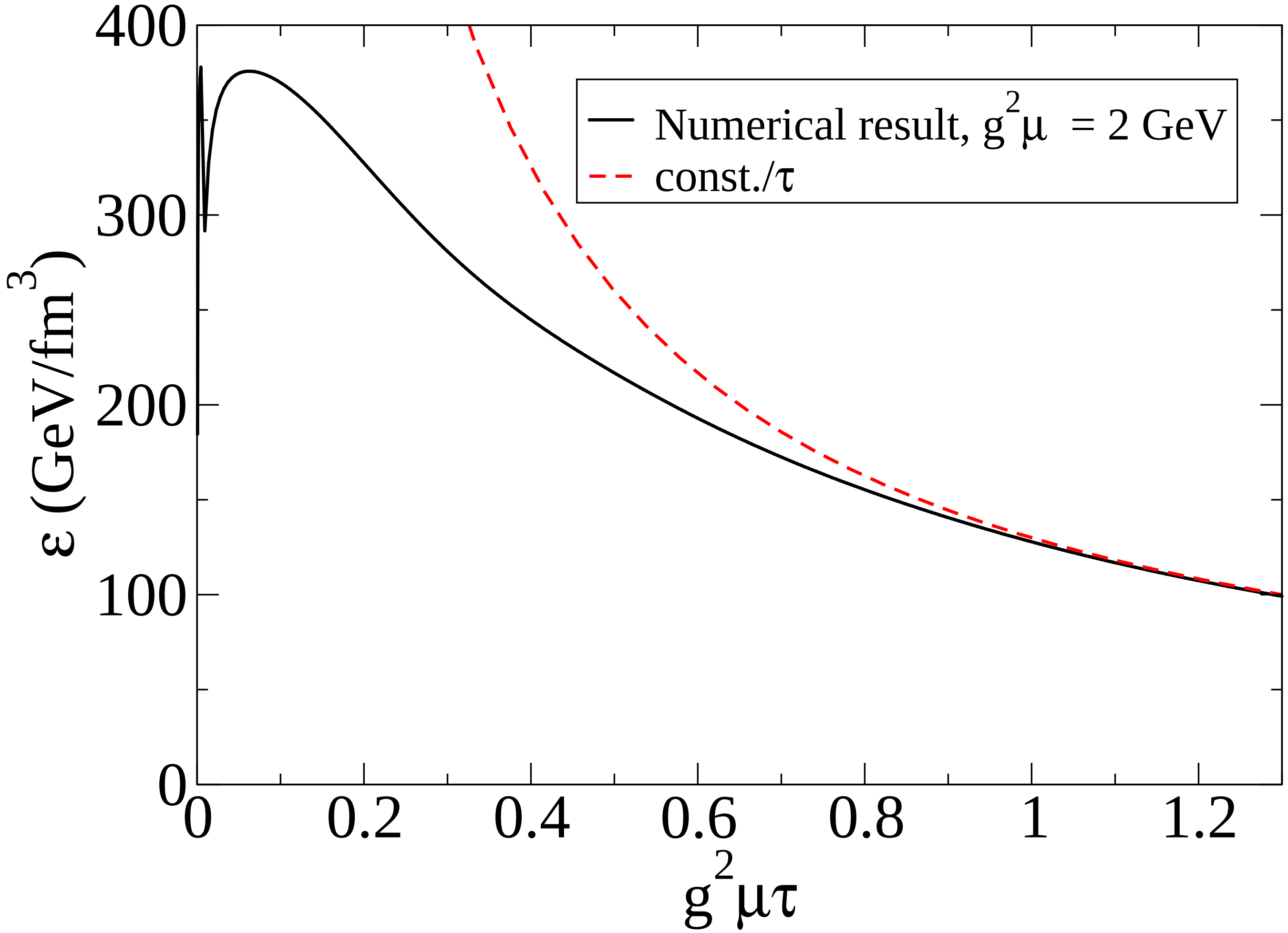
Set up the numerical computation on a, say, 512×512 transverse lattice (Krasnitz, Venugopalan, Lappi).Parameters: $g^2\mu, R_A$. Main output: energy density plotted as $dE/d\eta = \mathrm{V}\epsilon = \pi R_A^2 \tau\, \epsilon$:



$$g^2\mu = 2 \text{ GeV} \Rightarrow 1/g^2\mu = 0.1 \text{ fm}$$

Sudden rise at $\tau = 1/Q_s$, then $\epsilon\tau =$ const, no thermalisation, other physics.

But you can as well plot $\epsilon(\tau)$:



$\Rightarrow$ gluon production is instantaneous, all the action is on light cone.

Creation of little bang; followed by thermalisation, expansion, hadronisation,...

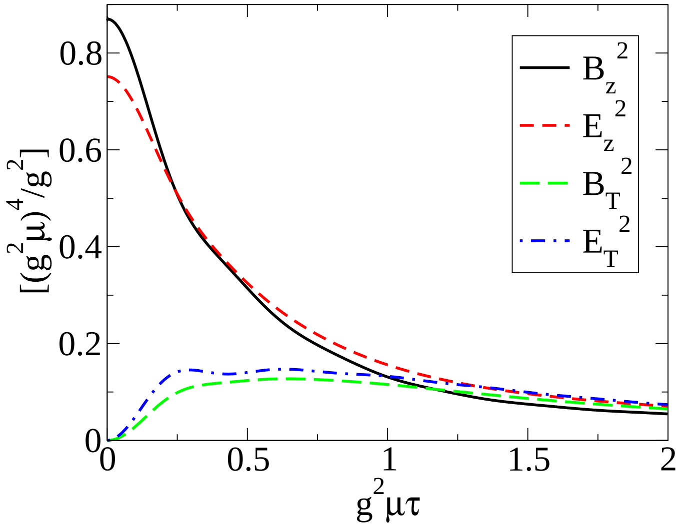
Find analytically:

$$\epsilon(\tau = 0) = \langle \int \frac{d^2\mathbf{x}_T}{\pi R_A^2} \frac{H(\mathbf{x}_T)}{\tau}|_{\tau=0} \rangle$$

$$\frac{H(\mathbf{x}_T)}{\tau}|_{\tau=0} = g^2(\delta_{ij}\delta_{kl} + \epsilon_{ij}\epsilon_{kl})\mathrm{Tr}[A_i^{(1)}(\mathbf{x}_T), A_j^{(2)}(\mathbf{x}_T)]\,[A_k^{(1)}(\mathbf{x}_T), A_l^{(2)}(\mathbf{x}_T)]$$

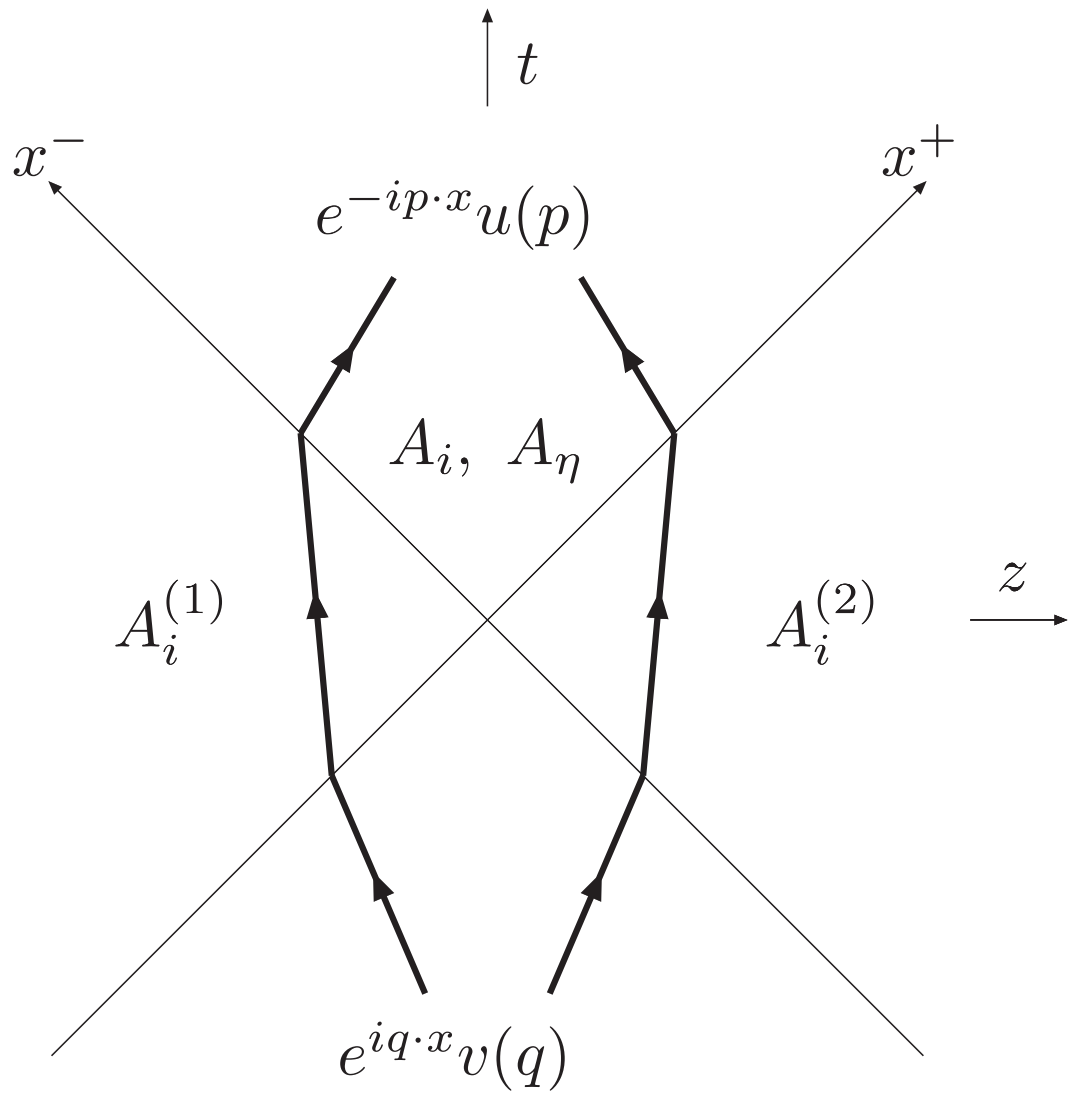
$$A_i = \frac{i}{g} U\partial_i U^\dagger, \quad U = e^{i\Lambda}, \quad -\partial_T^2\Lambda = g\rho \quad \rho = \text{stochastic source}$$

The initial energy density of little bang is given by the ensemble average of Tr product of two commutators of vacuum fields



Lappi-McLerran

Now that you have A_μ, does it produce $q\bar{q}$ pairs? Strong or time dependent fields produce particles.



The matrix element is

$$M_\tau(p,q) \equiv \int \frac{\tau \mathrm{d}z \mathrm{d}^2\mathbf{x}_T}{\sqrt{\tau^2+z^2}} \phi^\dagger_\mathbf{p}(\tau,\mathbf{x})\gamma^0\gamma^\tau\psi_\mathbf{q}(\tau,\mathbf{x}) \ .$$

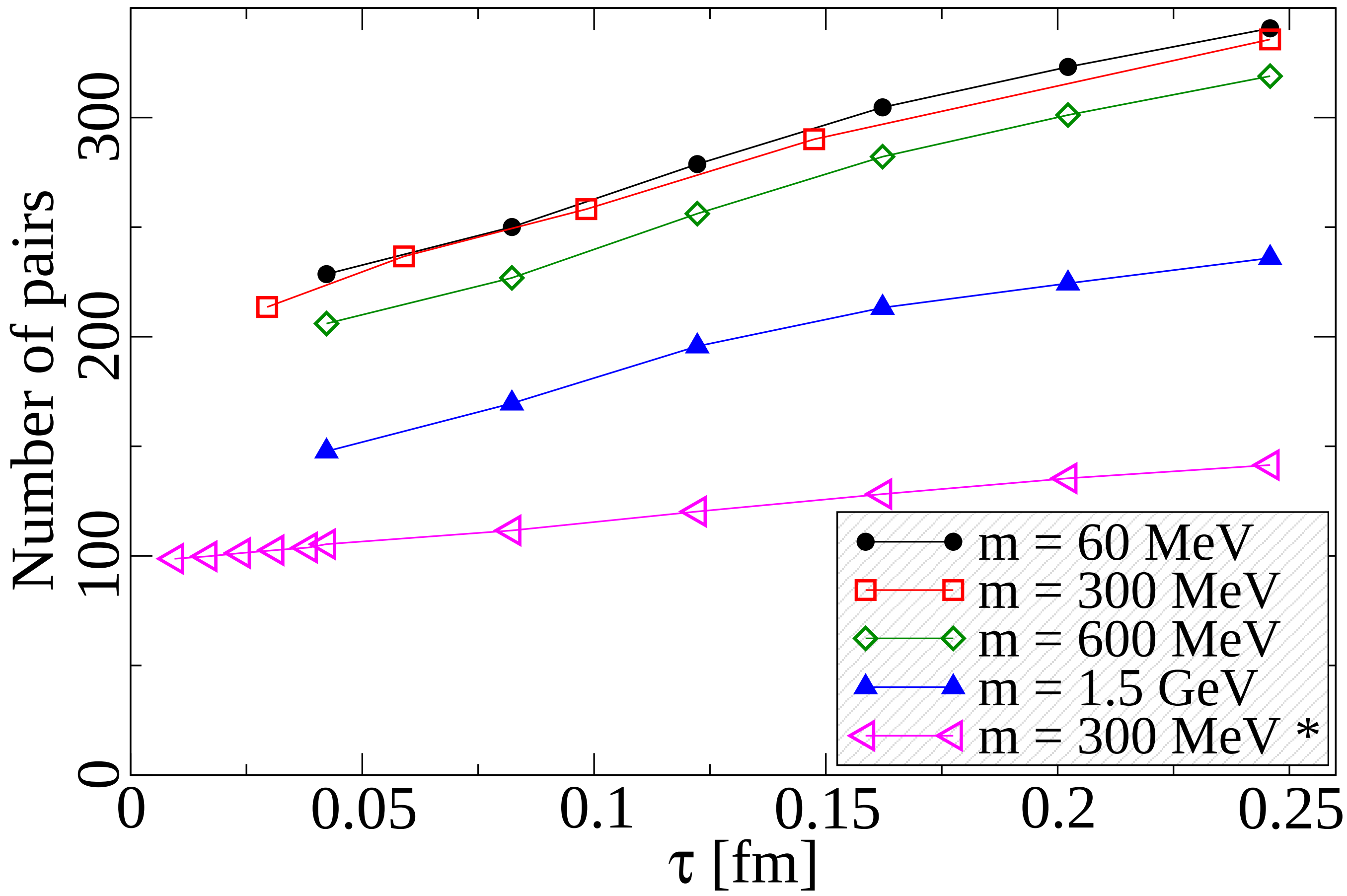
Now you have to set up a truly 1+3 d computation for integrating $\psi_\mathbf{q}(\tau,\mathbf{x})$ using Dirac.
F. Gelis, K. Kajantie, T. Lappi, hep-ph/0508229, PRL

Lattice spacing: $(N_T a)^2 = \pi(6.7\,\mathrm{fm})^2 \Rightarrow a = 12\,\mathrm{fm}/N_T \approx 0.05$ fm.

Number count: $\psi^c_\mathbf{q}(\tau,\mathbf{x})$ has $180^2\times 400$ numbers for $\mathbf{x}$, 3 for $c=3$ colors, 2·4 for ψ, a total of 1.2 GB single precision. This set is integrated forward in steps of $d\tau = 0.02a$ in 500 steps to get to $\tau = 0.25$ fm.

Warning: Maybe one should use energy eigenstates of the Hamiltonian with exact A^μ, not free ones!

$q\bar{q}$ pairs are also produced instantaneously and their number is LARGE!:



$g^2\mu = 2$ GeV ("LHC"), lowest curve $g^2\mu = 1$ GeV ("RHIC")

RHIC phenomenology

- Standard: Need 1000 partons, if these all gluons need $g^2\mu = 2$ GeV

- Alternative: Need 1000 partons, above results imply that $g^2\mu = 1.3$ GeV giving 400 gluons, $100N_f$ quarks, $100N_f$ antiquarks, close to thermal ratio $N_g/N_q = 32/9N_f$.

Thus also instant chemical thermalisation!?

Loopholes:

- Maybe need exact wave functions?
- Maybe the gluons produced by the classical gluon field also have to be included?

Conclusions

- Gluons dominate the wave function of a fast-moving hadron. Parametrically, pairs are suppressed by g^2 from the $q + \bar{q} \to g$ vertex $\Rightarrow$ Little bang is initially far from chemical equilibrium
- However, $g \approx 2$, little bang is very non-perturbative and our numerical results suggest early chemical equilibrium
- Theoretical loopholes exist and this is an issue which can only be resolved experimentally
- Experimental handle: thermal dilepton production
- Matching to heavy quark production?